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Selection of Appropriate Generation IV Nuclear Reactor Development: A Systems Engineering Approach

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1. Introduction

The Generation IV International Forum (GIF), an international organization founded in 2001, was initiated by the US Department of Energy aimed at advancing nuclear technology to meet future energy demands. It is a collection of 14 countries committed to joint development and cooperation in research for the next generation of nuclear energy systems (Gen IV). In 2002, GIF (then representing 10 countries) selected six (6) reactor technologies to be further developed on the basis of being safe, sustainable, cost-effective, and resistant to weapons proliferation [1]. Nowadays, there are several designs of Gen IV nuclear power plants (NPP) but few will be deployed due to strategic, economic, and even political reasons. Such factors posed a challenge in selecting an ideal Gen IV technology to be implemented. In this paper, selection criteria for implementing an appropriate Gen IV NPP program is developed for use in a systems engineering approach for decision making.

2. Generation IV Nuclear Systems

This section briefly discusses the six Gen IV nuclear systems selected by GIF [2]. The design concepts of these NPPs vary from neutron spectrum, fuel cycle type, temperature, and sizes to name a few. Table I lists some of these features.

2.1. Very-High-Temperature Reactor (VHTR)

VHTR is a thermal reactor cooled by helium gas and moderated by graphite (solid, can be recycled). The core outlet temperature (COT) of over 900°C and aiming for 1000°C enables the production of hydrogen for other co-generative industrial applications. VHTR is a small modular reactor (SMR) that has potential for high burn-up, complete passive safety, low operation and maintenance (O&M) cost, and modular construction that could partially compensate the loss of economies of scale. Although its basic technology has been established in former high-temperature gas reactors with hundreds of operation hours, the main research needs for VHTR are fuel, materials, and hydrogen production.

2.2. Molten Salt Reactor (MSR)

MSR is the only Gen IV reactor that utilizes liquid fuel (uranium is dissolved in the fluoride salt coolant) which circulates through the graphite core channels (also acts as moderator). This novel feature provides the foundation for an enhanced safety profile based on low pressure operation, eliminating the need for solid fuel fabrication and handling criticalities. Compared with solid-fueled reactors, MSR systems offer far more complete and efficient fuel consumption having lower fissile inventories and large negative reactivity feedback. Such characteristics may enable MSRs to have competitive economics, but needs more research and development (R&D) works in fuel treatment, materials, and reliability.

2.3. Super-Critical-Water Cooled Reactor (SCWCR)

SCWR, considered to an evolution of actual boiling water reactor (BWR), is a high-temperature and very high-pressure water-cooled reactor which operated above the thermodynamic critical point of water, giving a higher net electrical efficiency (10% higher than BWR). The super-critical water directly drives the turbine without the need for any secondary steam system (e.g. steam generator, dryer, recirculating system, etc.), thus improving economics because of plant simplification resulting in potential cost reductions of 30% compared with present pressurized-water reactors (PWR). With operational experience and passive safety

Table I: Gen IV reactor system designs

	Coolant	COT (°C)	Neutron Spectrum	Fuel Cycle	Size (MWe)	Net electrical efficiency (%)	Hydrogen production	Economics [3]
VHTR	helium	900-1000	thermal	open	250-300	50	yes	high
MSR	fluoride salts	700-800	fast	closed	1000	44-50	feasible	low
SCWR	water	510-550	thermal / fast	open / closed	300-1500	44	no	high
GFR	helium	850	fast	closed	1200	45-48	yes	medium
SFR	sodium	500-550	fast	closed	50-1500	> 40	no	medium
LFR	lead or Pb-Bi	550-800	fast	closed	20-1000	45	yes	medium

features similar to those of BWRs, R&D is still needed on materials and thermal-hydraulics.

2.4. Gas-Cooled Fast Reactor (GFR)

Like other helium-cooled reactors, GFR will be a high-temperature and a fast-spectrum reactor that employs similar technology with VHTR, which is suitable for electricity generation and thermochemical hydrogen production for industrial applications. With a high COT of 850°C, it enables an elevated efficiency for helium Brayton cycle. GFR is the only Gen IV design with no operating antecedent and experience, Moreover, the main R&D needs for this reactor system are fuels, thermal-hydraulics, and material as core internals are exposed to high temperatures and elevated irradiation.

2.5. Sodium-Cooled Fast Reactor (SFR)

SFR is a fast reactor that uses liquid sodium as coolant allowing high power density with low coolant volume operated at low pressure. Having a high specific heat, sodium is a good coolant and is less corrosive than lead, but it chemically reacts with water and air, so a sealed coolant system is required. SFR builds on 390 reactor-years of operational experience and remains the forefront as the main technology of interest in GIF. Three variants are proposed: a 50-150 MWe modular-type; a 300-1500 MWe intermediate-to-large size pool-type; and a 600-1500 MWe large size loop-type reactor. While SFR is the most researched type of fast reactor, R&D is focused on safety in loss-of-coolant scenarios, fuels and its handling, and advanced recycle options.

2.6. Lead-Cooled Fast Reactor (LFR)

LFR is a flexible fast neutron reactor that can be fueled by depleted uranium or thorium matrices. It is cooled by liquid lead or lead-bismuth eutectic (LBE) which has a high boiling point, does not react to water and air, and has an excellent neutron and thermos-fluid-dynamic properties. Compared to LBE, pure lead is more abundant, less expensive, and less corrosive at high temperature. A wide range of unit size envisaged from a battery type producing 20-180 MWe, to modular-types producing 300-400 MWe, and to large size plants of 1400 MWe. COT of 550°C is achievable but 800°C is aimed to enable hydrogen production. The main research needs for LFR are fuels and advanced materials.

In 2014, GIF Technology Roadmap Update publication [4] confirmed the choice of the six nuclear systems mentioned above, and focused on their R&D goals. It also suggested that SFR, LFR, and VHTR reactor technologies are most likely to be deployed first, while MSR and GFR are the farthest from demonstration phase. Moreover, the European Commission in 2010 launched the European Sustainable Nuclear Industrial Initiative (ESNII) to support three Gen IV fast reactors for deployment (SFR, GFR, and LFR) to promote low-carbon energy technologies, with a total estimated cost of €10.8 billion [5].

3. Selection Methodology Design and Development

In developing the selection criteria for appropriate Gen IV reactor technology from a systems approach, several requirements are taken into consideration such as design, performance, stakeholder, and system functions. The process is supplemented by comprehensive literature reviews on the different Gen IV technologies, mostly from the GIF annual reports and technology roadmap documents [1, 2, 4]. The basis of the requirements analysis, goal setting, and criteria development is the evaluation and selection methodology when GIF screened hundreds of proposal for Gen IV systems in 2001, resulting to the six Gen IV reactors being developed currently.

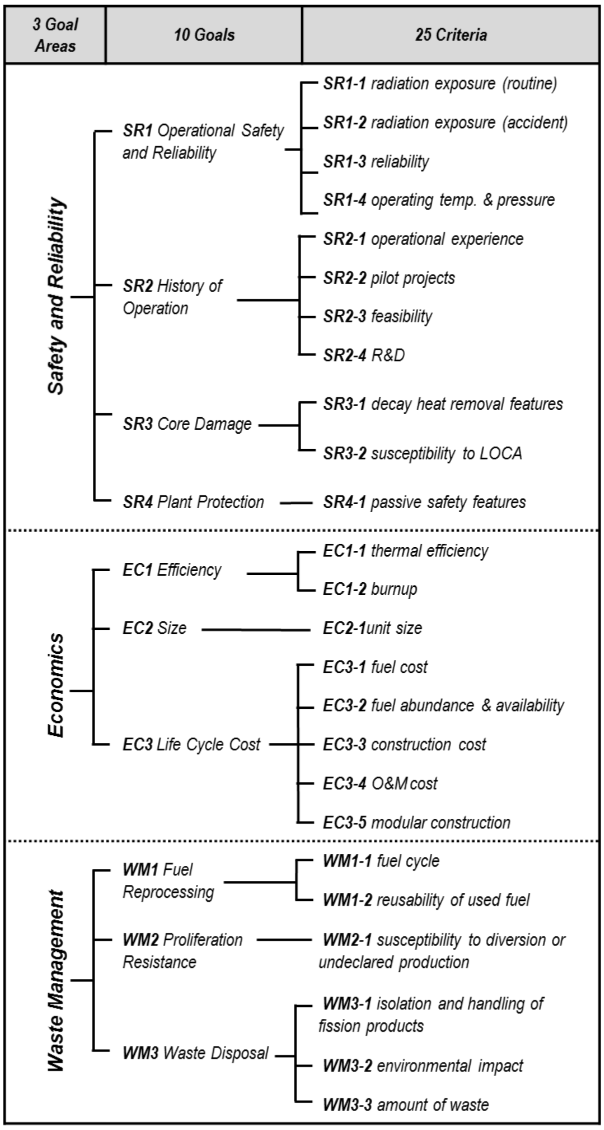

Figure 1. Roll up of criteria, goals, and goal areas.

Figure 1 presents the goal areas with goals arranged under them, and the criteria assigned to the various goals. The 10 goals for Gen IV systems are defined in the three broad areas of Safety and Reliability, Economics, and Waste Management. Safety and Reliability goals focus on safe and reliable operation, history of operation, improved accident management, and securing nuclear facilities. Economics goals focus on energy production size and efficiency and competitive life cycle costs. Lastly, Waste Management goals focus on used fuel reprocessing, disposal of radioactive waste, and controlling nuclear materials.

The goal areas, goals, and criteria are in line with the GIF's motivation of identifying systems that make significant technological advances; adequately address the mission of electricity generation and hydrogen production; provide some overlapping coverage of capabilities and research areas to avoid unnecessary expense of duplicated major facilities and research efforts; and accommodate the range of national priorities of the countries that are part of GIF.

The first goal area of safety and reliability is the most important priority in selecting a nuclear energy system. It ensures normal operation and prevents off-normal situations to deteriorate into severe accidents. The operating temperature and pressure of a nuclear system is also weighted as high-temperature system may require a large cooling mechanism and high-pressure system poses explosion risks during accident scenarios. History of operation is added as a criteria, which is originally not in GIF's metric. The viability and success of a new nuclear program cannot rely only upon on its technology but also requires proven experience from pilot project prototypes and research demonstration. Furthermore, plant protection goals would guarantee that future nuclear plants are designed to withstand external events, and highly secure it from internal threats through passive safety systems, that would eventually increase the public confidence on the safety of nuclear infrastructures.

The second goal area of economics focuses on the economic competitiveness of future nuclear system with efficiency and reactor size are a great factor in implementing Gen IV program. Fuel abundance & availability is included as a criteria (not part of GIF's metric), and should have a reasonably high weight factor for the reason that Gen IV is initiated in the first place because a shortage of uranium is expected in the upcoming decades according to several energy foresight studies. Although one of GIF's motivations is the co-generation of hydrogen in Gen IV reactors, that criteria is ignored due the reasons that it needs further study on the development of heat exchangers, coolant gas ducts and valves necessary to isolate the nuclear island from the production facilities. It would require additional structures and manpower which are not beneficial in an economic and radiation-exposure safety points-of-view. The original GIF criteria of overnight construction cost is not reflected in this developed metric as this risk to capital is out-of-scope and not attributed to the technological nature of Gen IV reactors but dependent on the construction performance of an implementing country or company.

Lastly, the criteria in the third goal area of waste management are conceptually adapted from the GIF metric. Fuel reprocessing and waste disposal criteria ensures to maximize the resource base and minimize high-level wastes to be sent to repositories. Additionally, proliferation resistance criteria would prevent the use of civilian nuclear energy systems for nuclear weapons proliferation. While some GIF initial criteria of great importance aimed to ensure operational safety and reliability are adopted, a number of it with subjective nature are disregarded. A new set of goals and criteria are also developed and introduced into the metric. Overall, these goal areas are aimed to be an effective mechanism in selecting an ideal Gen IV nuclear system to achieve long-term and sustainable goals that meets future energy demands.

4. Conclusion

In this paper, some selection criteria for implementing Gen IV technology is developed. It involves three goal areas with 10 goals and 25 criteria under them. It is important to note that metrics and the corresponding weight factors for each criteria has not been set due to its subjective nature and will be based on technology experts' determination or a country's suitable need for such nuclear systems.

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